Precision EW Measurements at the Large Hadron Collider at 8 TeV and 13-14 TeV

($\sin^2\theta_W^{eff}$, $\sin^2\theta_W^{on\text{-}shell}$, $M_W^{indirect}$, M_W^{direct})

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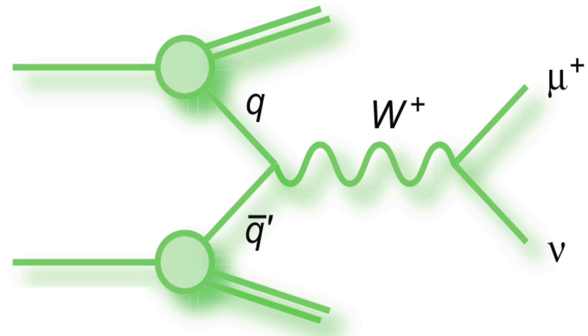
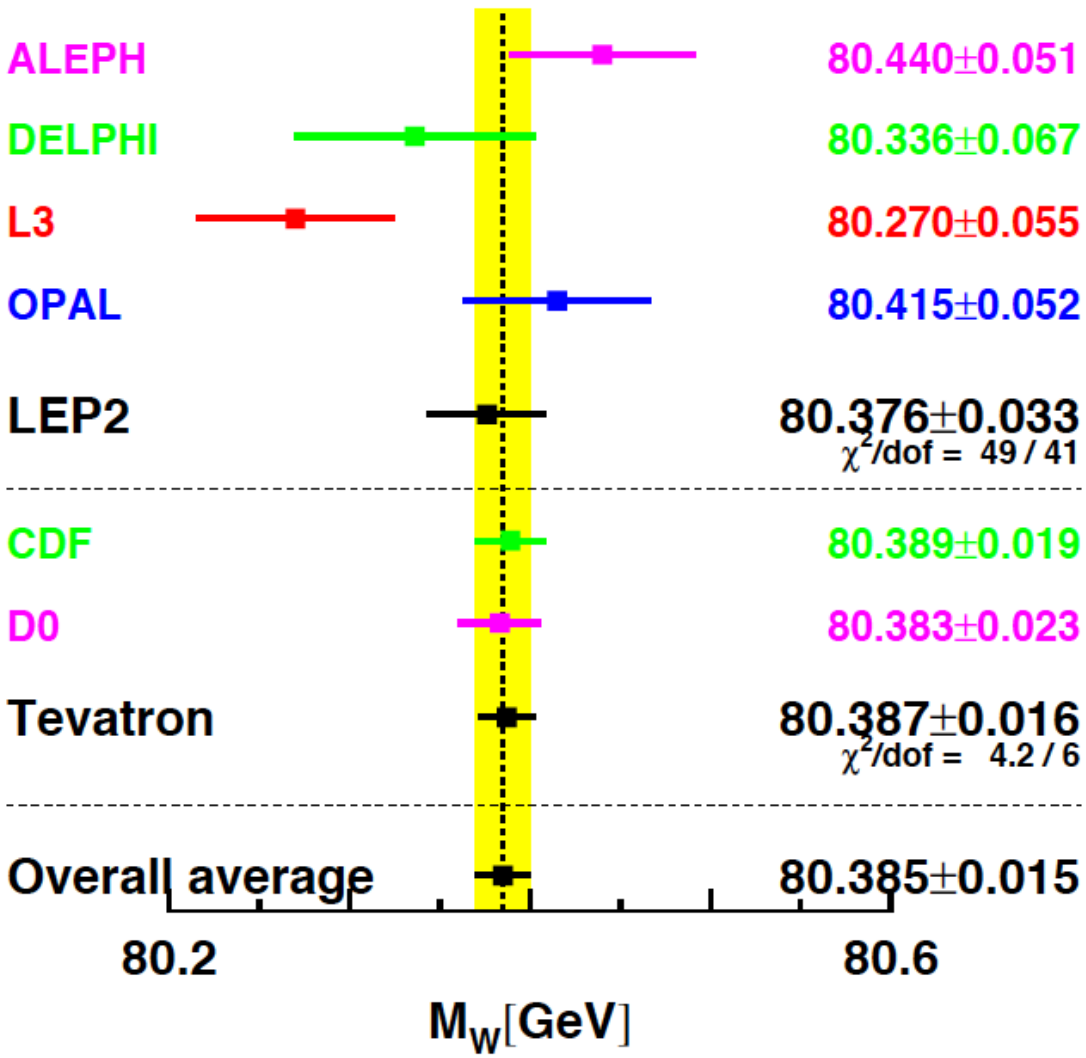
SM session of the
"Experimental Challenges for the LHC Run II" KITP workshop
Monday March 28, 2016

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-w-mass.pdf

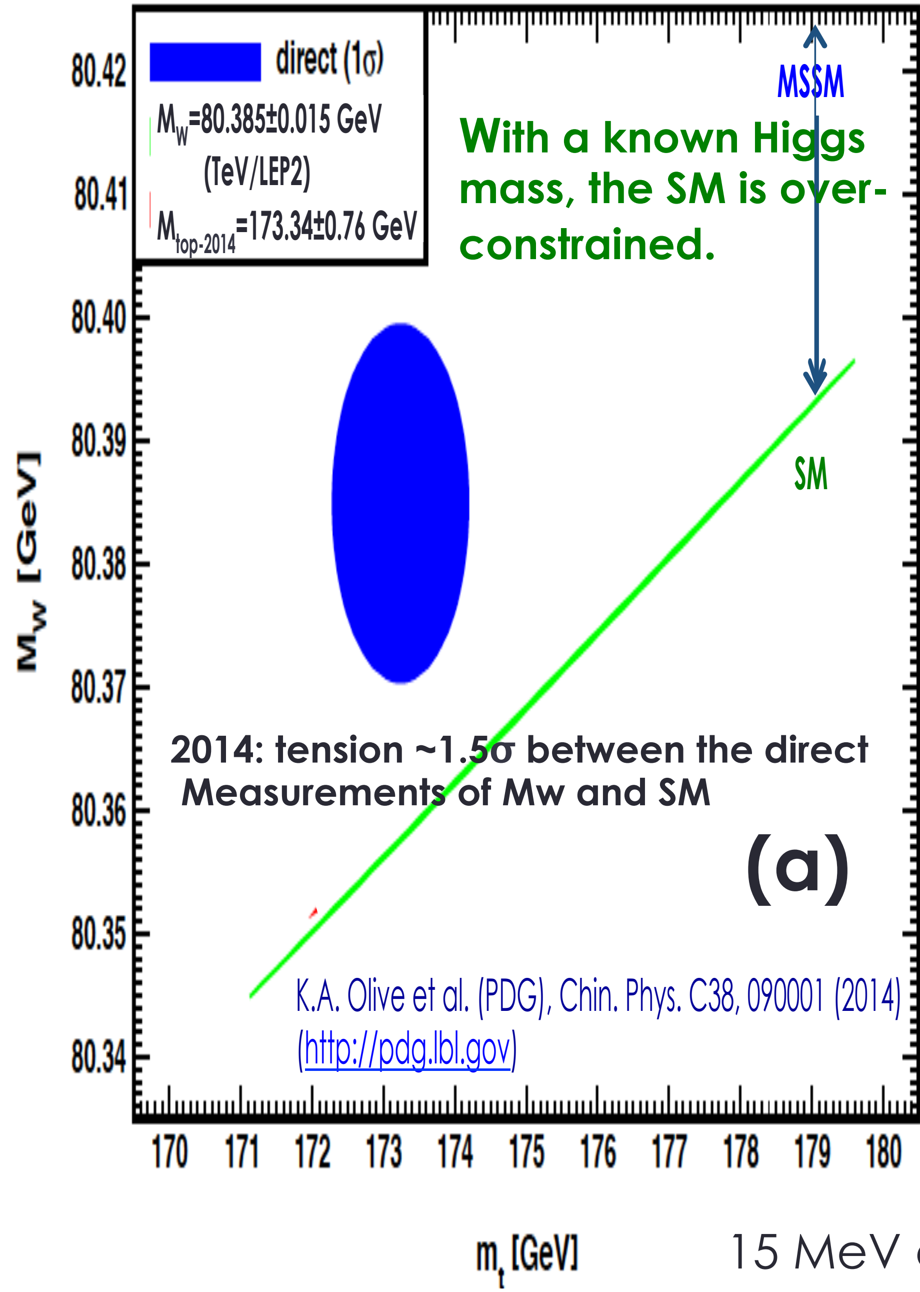


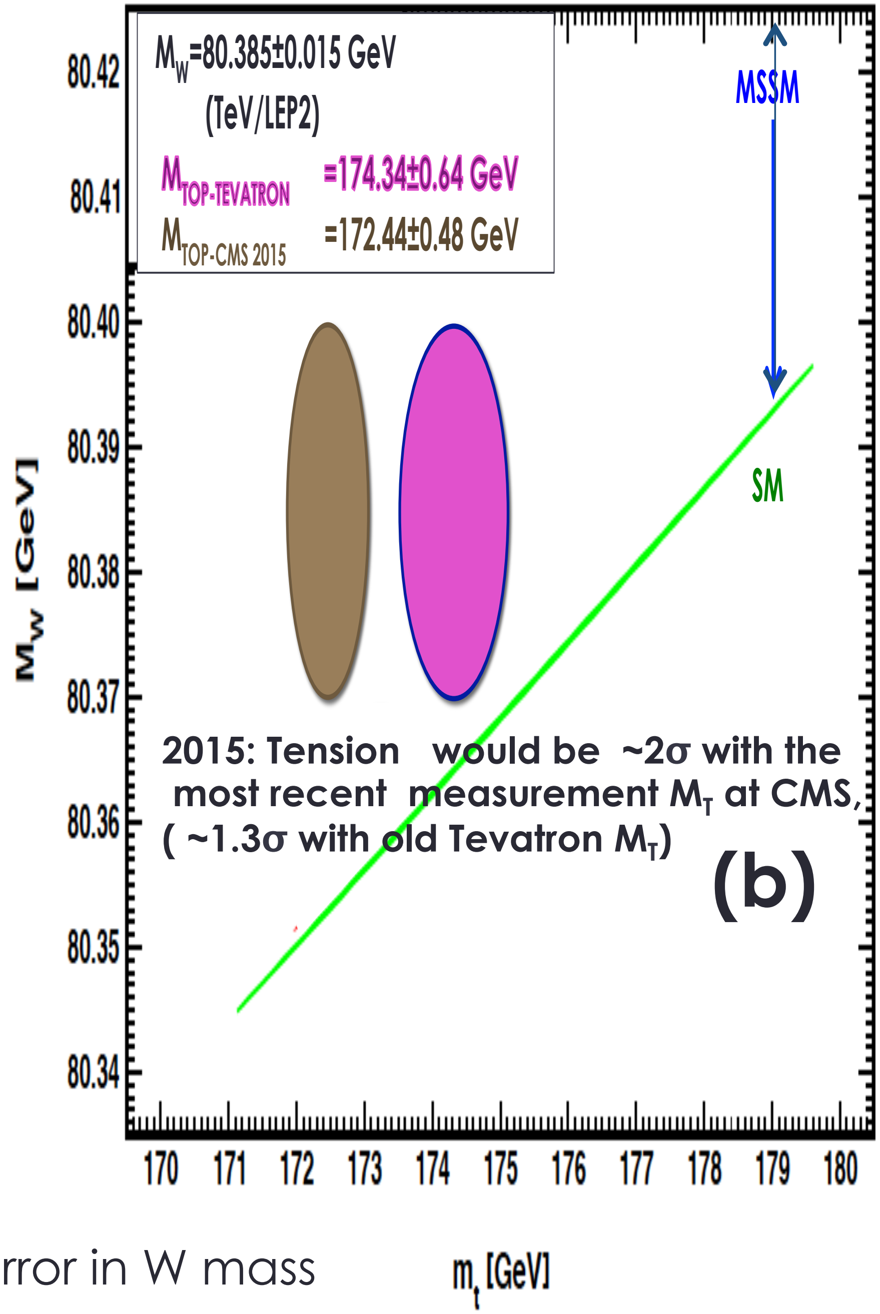


Most recent Tevatron M_W^{direct} measurements (CDF and Dzero)

ΔM_W^{direct} ~20 MeV

Standard Model vs Super symmetry

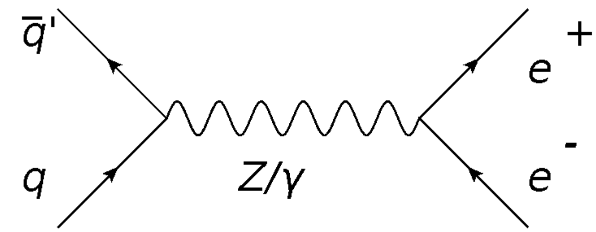




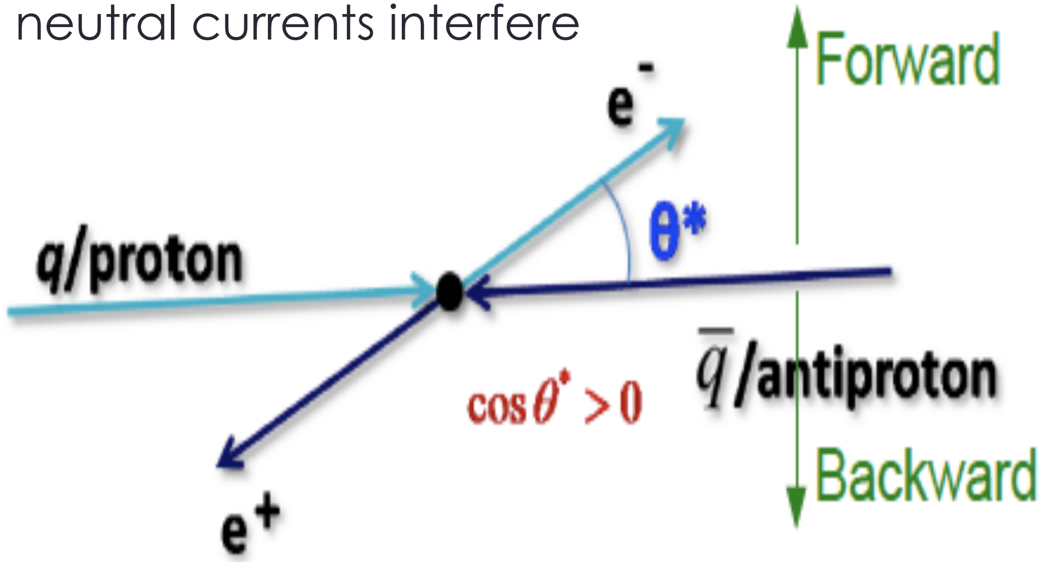
15 MeV error in W mass

Drell-Yan A_{FB}

A_{FB} for e^+e^- or $\mu^+\mu^-$ pairs in the Z boson Region is sensitive to the effective EW mixing angle $\sin^2\theta_{eff}$



The axial and vector neutral currents interfere



Define Forward-Backward asymmetry:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\sin^2\theta_{eff}^{lept} \simeq 1.037 \cdot \sin^2\theta_W \quad [\text{ ZFITTER } \kappa_e(\sin^2\theta_W, M_Z) \text{ form factor }]$$

(*above relation is approximate*) one needs to include complex EW radiative correction form factors in the theory predictions for A_{FB} to extract the on-shell $\mathrm{Sin}^2\theta_W$

$$\mathrm{Sin}^2\theta_W = 1 - M_W^2 / M_Z^2$$

Indirect Measurement of W mass

M_W can also be determined indirectly via the relation

$$\sin^2\theta_W^{on\text{-}shell} = 1 - M_w^2 / M_z^2$$

±0.00040 error in $\sin^2\theta w$ is equiv. to ±20 MeV error in Mw (indirect)

Both $\sin^2\theta_W^{on\text{-}shell}$ and $\sin^2\theta_{eff}^{leptonic}(M_z)$ can be extracted from Drell-Yan forward-backward asymmetry (Afb) if we include EW radiative corrections. $M_w^{indirect}$ can be extracted from $\sin^2\theta_W^{on\text{-}shell}$

- If the SM is correct, then measurements of M_w^{direct} and $M_w^{indirect}$ should agree. Deviations may imply the possibility of new physics.

- Similarly different measurements of $\sin^2\theta_{eff}^{leptonic}(M_z)$ should also agree and deviations may imply new physics.

We are now able to minimize experimental systematic errors, as shown in the next few slides

→ Therefore, PDF uncertainties limit the precision of the measurements of $\sin^2\theta_W^{eff}$, $\sin^2\theta_W^{on\text{-}shell}$, $M_W^{indirect}$ and M_W^{direct} at the LHC.

→ We will show that Drell-Yan Afb provide further constraints on PDFS

Tevatron ee & μμ 9 fb^{-1}: $\sin^2\theta_{eff}(M_Z)$

DØ ee

$\sin^2\theta_{efff}$ = 0.23146 ± 0.00043(stat)
± 0.00008(syst)
±0.00017 (NNPDF2.3 PDFs NLO)

$\sin^2\theta_{efff}$ = 0.23146 ± 0.00047 (total)

CDF ee & μμ

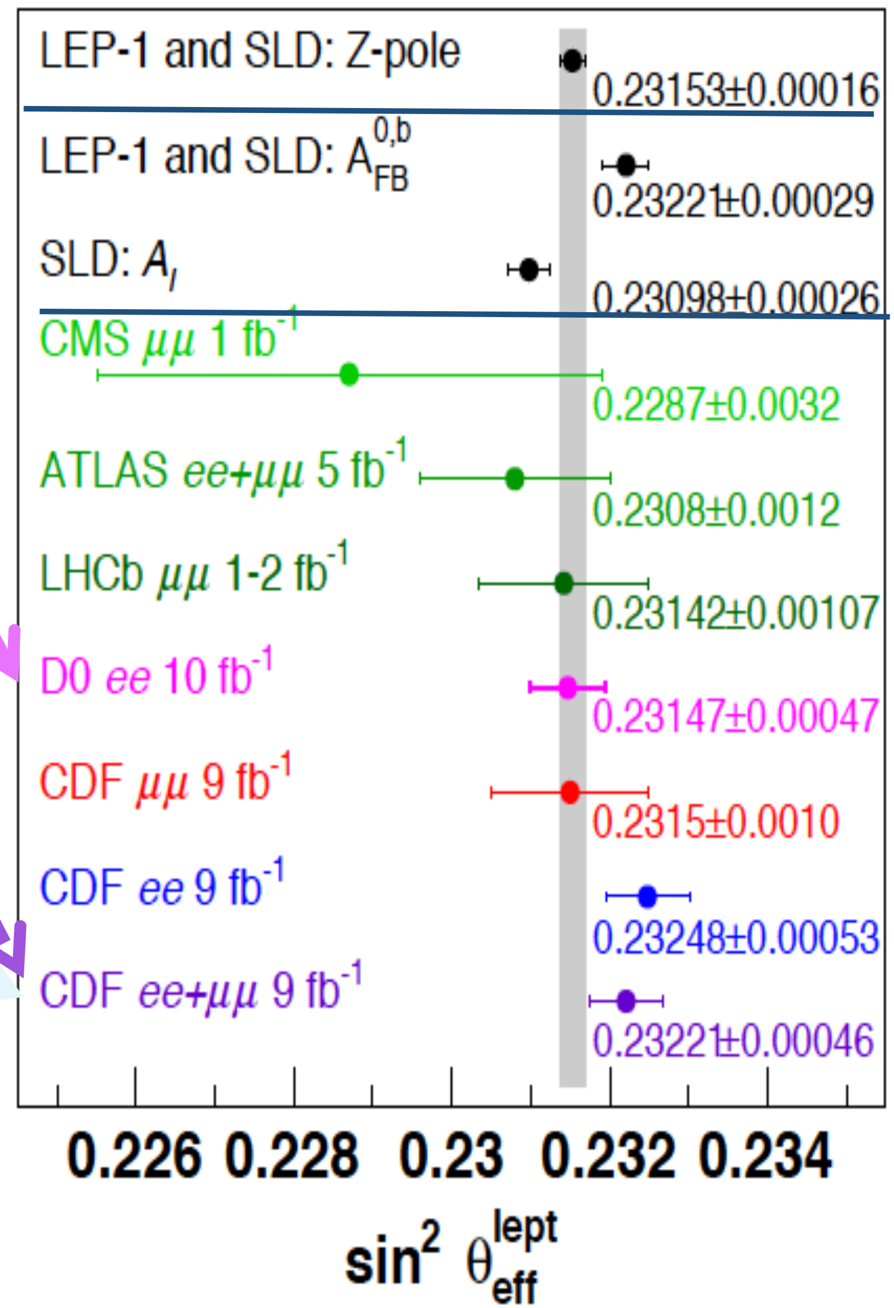
$\sin^2\theta_{eff}$ =0.23221 ± 0.00043(stat)
± 0.00005(syst)
±0.00016 (NNPDF3.0 PDFs NNLO)

$\sin^2\theta_{efff}$ = 0.23221 ± 0.00046 (total)

PDF errors smaller at the Tevatron than at the LHC.

ATLAS **$\sin^2\theta_{efff}$ =** 0.23080 ± 0.00050(stat) ± 0.00060(syst) ± **0.00090(pdf)**

Need to greatly reduce PDF errors at LHC (by a factor of 4 with respect to ATLAS)



CDF ee & μμ 9 fb^{-1} Indirect M_W measurement

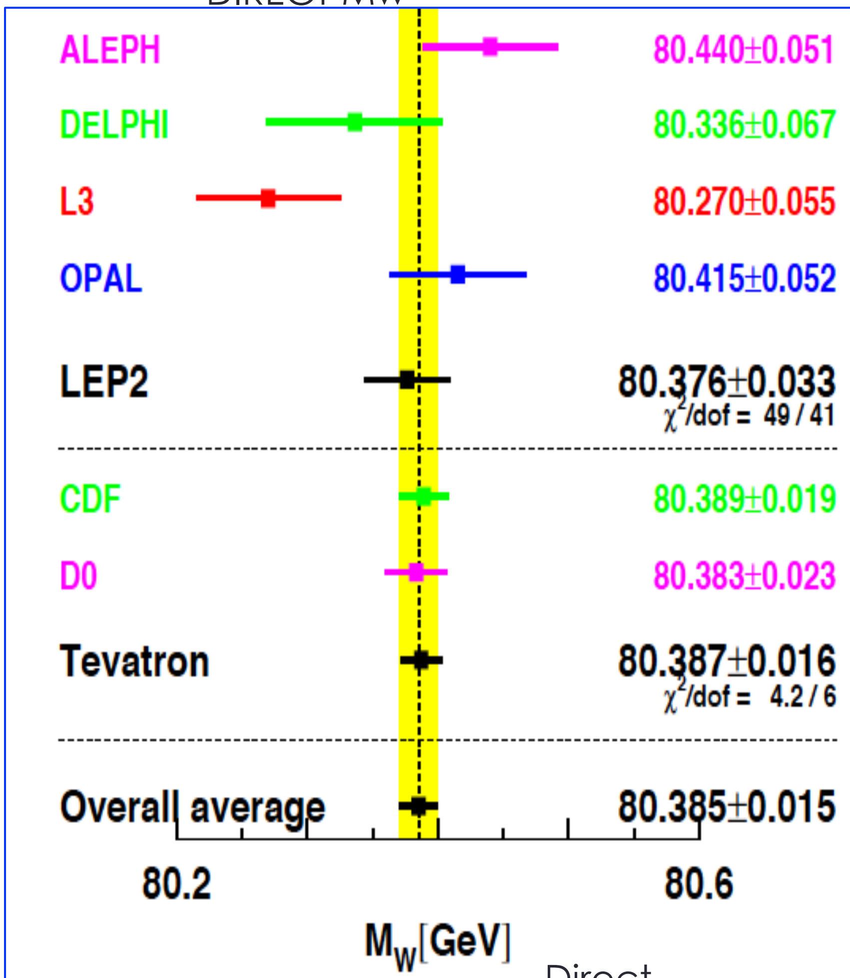
Aim at 10 MeV error in both direct and indirect Mw measurement at the LHC.

$$\sin^2\theta_{\rm eff}^{\rm lept} = 0.23221 \pm 0.00046$$

$$\sin^2\theta_W = 0.22400 \pm 0.00045 \quad \text{On-shell}$$

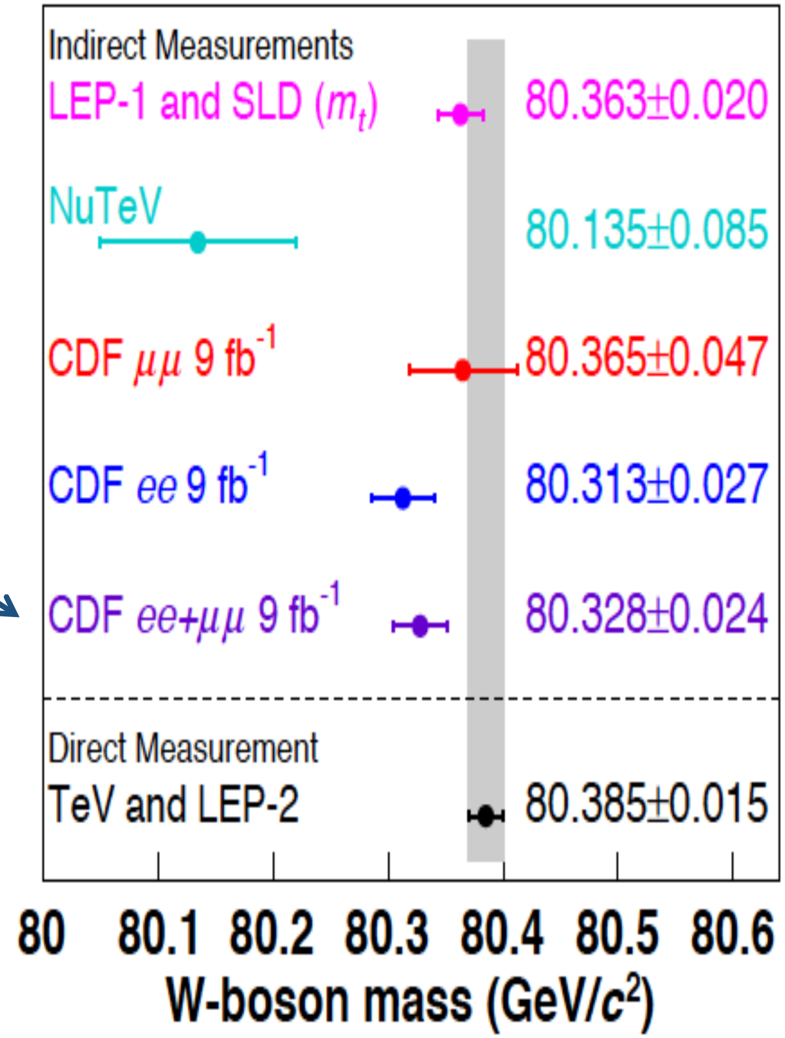
$$M_W(\text{indirect}) = 80.328 \pm 0.024\ \text{GeV}/c^2\,.$$

DIRECT Mw



Direct

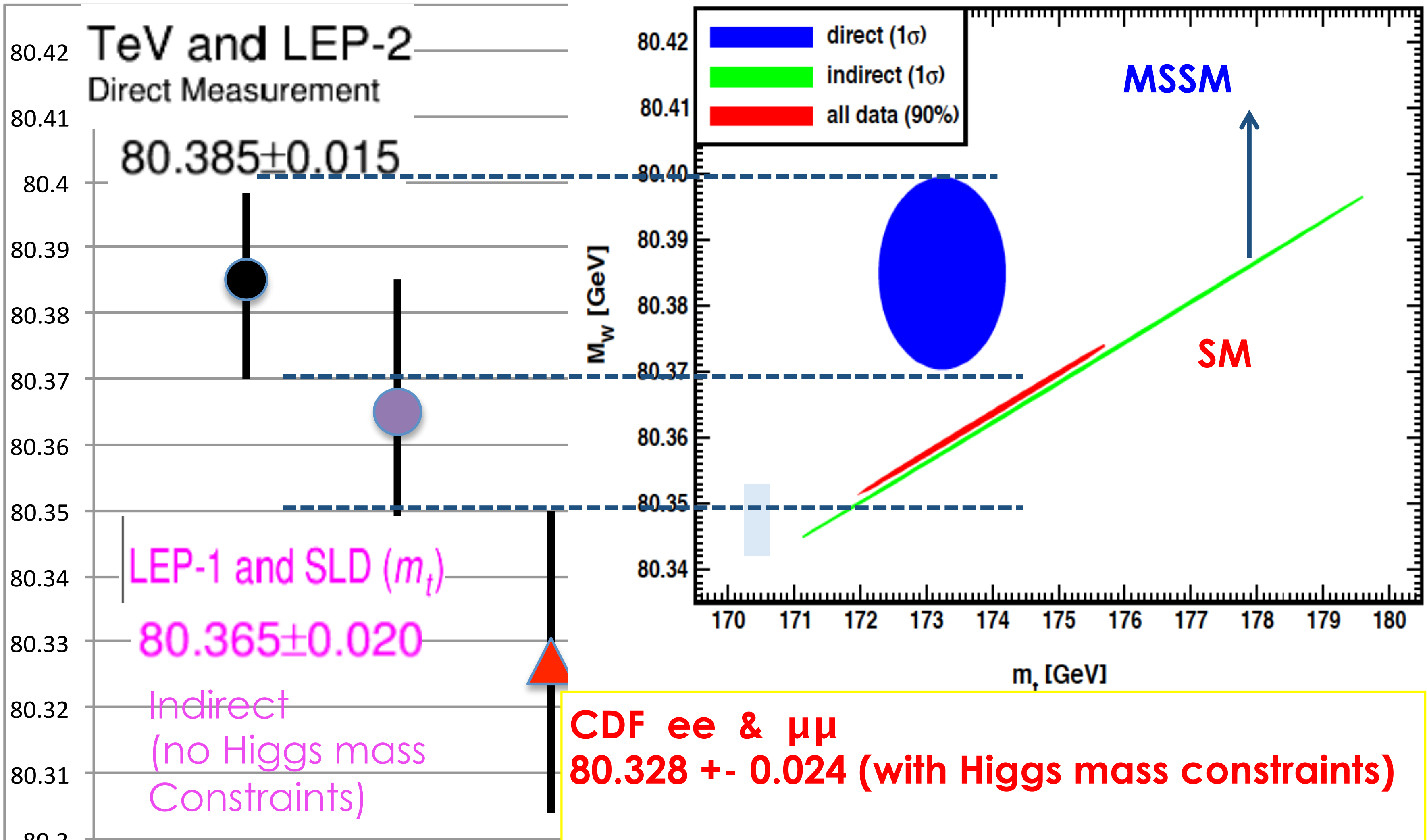
INDIRECT Mw



http://pdg.lbl.gov/2014/reviews/rpp2014-rev-w-mass.pdf

CDF ee & μμ 9 fb^{-1} Indirect M_W measurement

http://pdg.lbl.gov/2014/reviews/rpp2014-rev-standard-model.pdf
K.A. Olive et al. (PDG), Chin. Phys. C38, 090001 (2014) (http://pdg.lbl.gov)



CDF ee & μμ
80.328 +- 0.024 (with Higgs mass constraints)

CDF-D0 combination will reduce this by a factor of about 1.4

Precise Energy/Momentum Scale corrections

Systematic errors from momentum and energy calibration are now very small

New technique used for both $\mu^+\mu^-$ and e^+e^- for both data and hit level MC.
(Ref A. Bodek et al. Euro. Phys. J. C72, 2194 (2012))

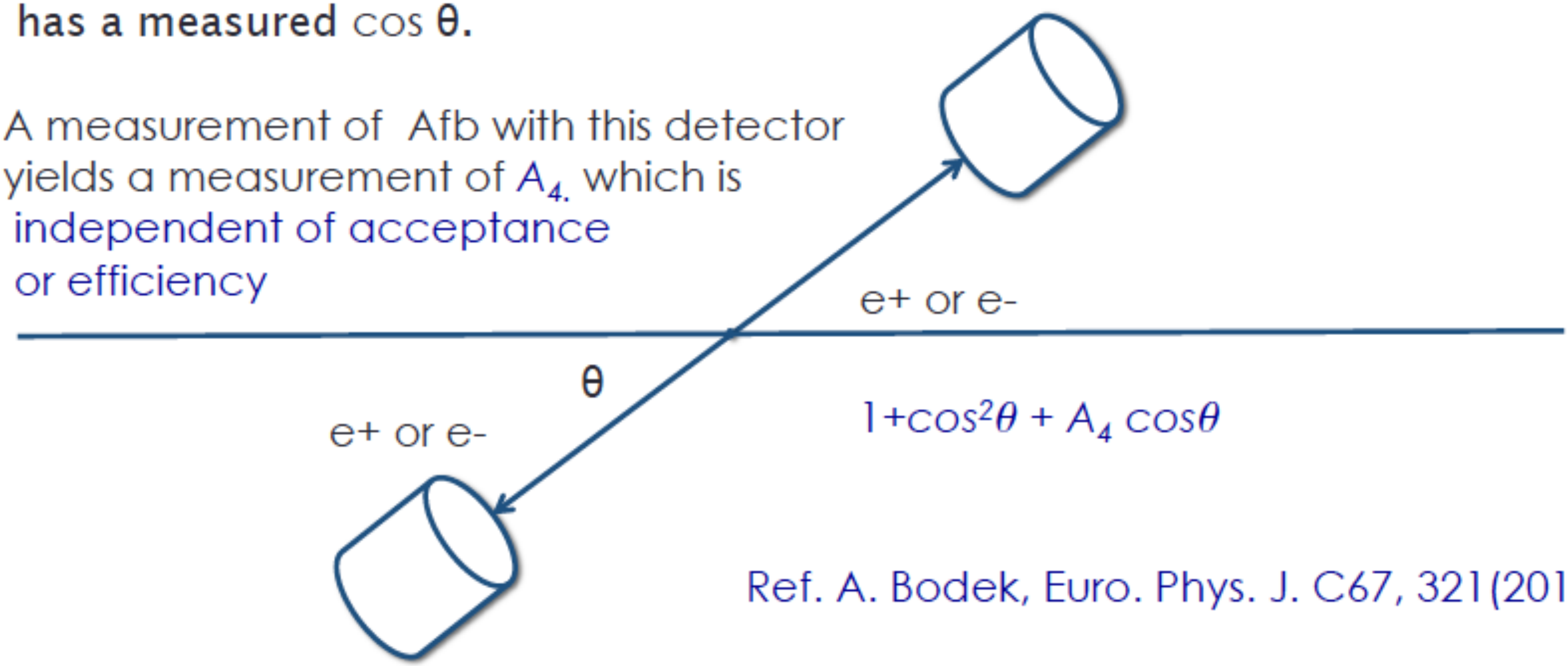
Step 1 : Remove the correlations between the scale for the two leptons by getting an initial calibration using Z events and requiring that the **mean $<1/P_T>$** of each lepton in bins of η, Φ and charge be correct.

Step2: The Z mass used as a calibration. The Z mass as a function of η,Φ, (and charge for $\mu^+\mu^-$) of each lepton be correct

- **Reference for muons:** Expected Z mass (post FSR) smeared by resolution (with acceptance cuts).
- **Reference for electrons:** Expected Z mass (post FSR + clustered FSR photons), smeared by resolution (with acceptance cuts).
- Now Used in CDF, CMS. A similar technique is used in Dzero.

Imagine a detector with acceptance for only one value of cos θ. **Each event has a measured** cos **θ.**

A measurement of Afb with this detector yields a measurement of A_4, which is independent of acceptance or efficiency



Ref. A. Bodek, Euro. Phys. J. C67, 321(2010)

cos **θ=1 yields best** measurement of A_4. cos **θ=0 yields no measurement of** A_4

We can combine measurements of A4 with different detectors at different cos(θ) by weighting events. Events with cos(θ)=0 have zero weight.

Events with cos **θ=1 have maximum weight. → obtain smaller statistical error.**

Afb (all cos **θ) = (3/8)** A_4 **→ No acceptance corrections needed.**

Minimize experimental acceptance and efficiency errors

Systematic errors from acceptance and efficiencies are now very small

New technique: event weighting method for A_{FB} analyses

Ref. A. Bodek, Euro. Phys. J. C67, 321(2010)

$$dN/d\cos\theta = 1+\cos^2\theta + A_0(M,P_T)\ (1-3\cos^2\theta)/2 + A_4(M)\cos\theta$$

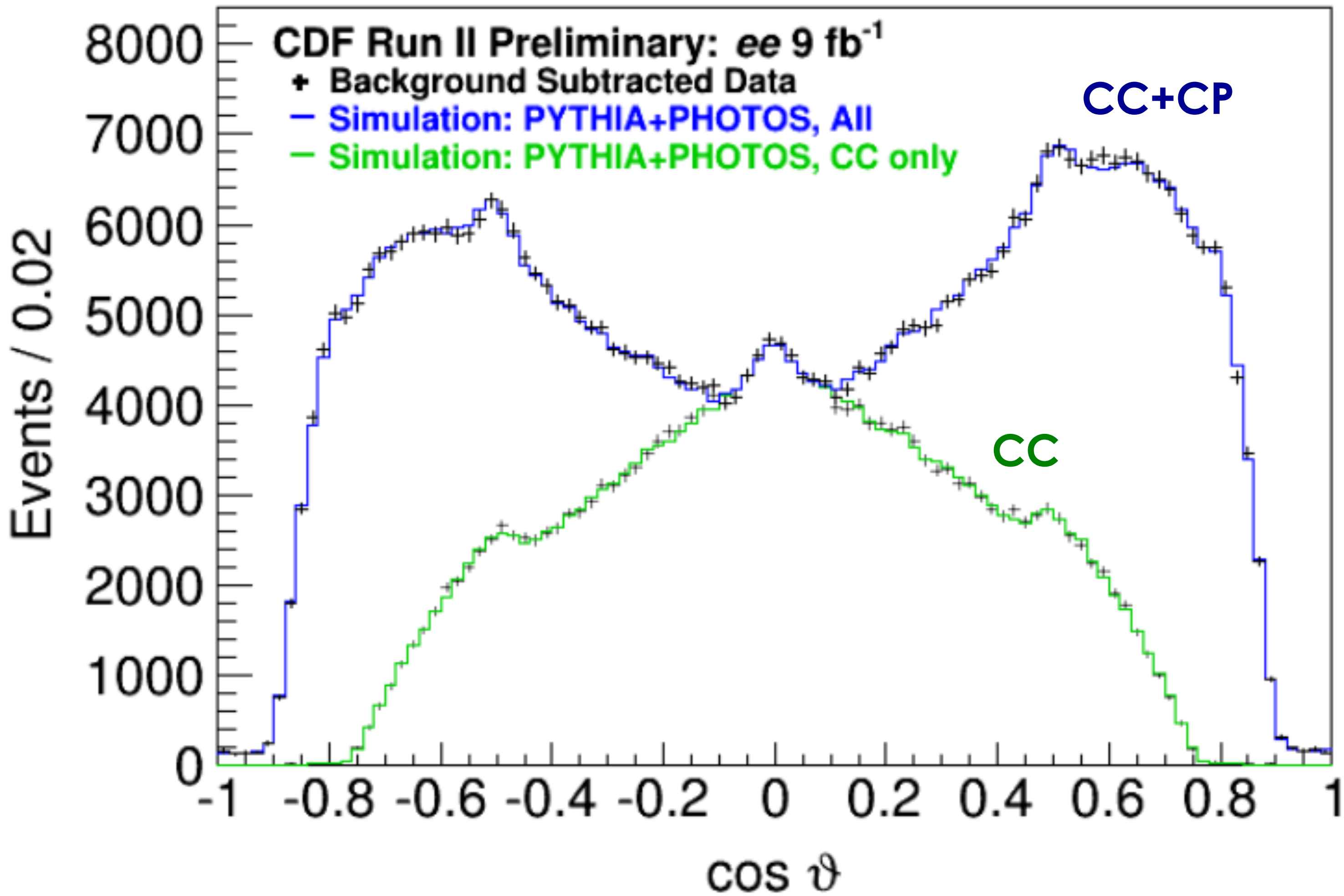
Angular event weighting is equivalent to extraction of $A_4(M)$ in bins of $\cos\theta$, and averaging the results.

Events at large $\cos\theta$ provide better determination of A4, so they are weighted more than events at small $\cos\theta$.

For each $\cos\theta$ acceptance and efficiencies cancel to first order in the measurement of A_4. Then set $A_{fb} = (3/8)A_4$

Statistical errors with event weighting are 20% smaller. Systematic errors largly cancel.

Event weighting does not correct for resolution smearing and final state radiation, which are included later in the unfolding using M.



The error in *Afb* is reduced if we have more acceptance at large **cosθ**,
Standard Afb method requires precise knowledge of acceptance and efficiencies.

Measure $A_4 \rightarrow A_{FB}$

What remains: Reducing PDF errors

PDF fits have a limited number of parameters and therefore cannot precisely describe PDFs in all regions of x and Q2 at the same time. In addition, sometimes experimental errors are inflated to account for inconsistencies between experiments at different regions of x and Q2.

- For Mw extraction from W data and $\sin^2\theta_{eff}$ extraction from Z data we are mainly interested in precise PDFs in the x and Q2 regions relevant for the production of W and *Z for a particular CM energy*.

  For the Tevatron only PDFs which are consistent (within errors) with W and Z production data at CDF or D0 are relevant.

  For LHC only PDFs which are consistent (within measurement errors) with W and Z production data at the LHC are relevant.

- We can further constrain the PDF using new precise LHC data that has not been used in the published PDF fits. (e.g. 8 and 14 TeV W asymmetry data).

- In addition, we have developed a way to include Drell-Yan Afb data to further constrain PDFs in this important x and Q2 region. (Afb data have never been included in any PDF fits before).

Example: Mw measurement at the Tevatron

From: Parton Distribution Uncertainty in the Measurement of M_W in Proton - Anti-proton Collisions, W.James Stirling, Alan D. Martin (Durham U.). Phys.Lett. B237 (1990) 551, DOI: 10.1016/0370-2693(90)91223-X

At the Tevatron, for valence-valence W production (for PT=0 W's), *when integrated over all rapidity,* the PT distribution of the lepton from W decay is given by an expression which is independent of PDFs.

$$\frac{dN^{e\mp}}{d\cos\theta^*} = \tfrac{3}{8}\,(1 \pm \cos\theta^*)^2 \qquad \cos\theta^* = \left(1 - \frac{4p_T^2}{M_W^2}\right)^{1/2}$$

$$\frac{1}{\sigma}\frac{d\sigma}{dp_T^2} = \frac{3}{2M_W^2}\left(1 - \frac{4p_T^2}{M_W^2}\right)^{-1/2}\left(2 - \frac{4p_T^2}{M_W^2}\right)$$

→f independent of PDFs
For full acceptance

However, if the detector has limited lepton rapidity coverage (R) the expression is modified:

$$\frac{1}{\sigma}\frac{d\sigma}{dp_T^2} = \frac{3}{2M_W^2}\left(1 - \frac{4p_T^2}{M_W^2}\right)^{-1/2}\left(2 - \frac{4p_T^2}{M_W^2}\right)F(p_T)\,,$$

Where F(PT) is PDF dependent

PDF errors in Mw measurement at the Tevatron

$$\frac{1}{\sigma}\frac{d\sigma}{dp_T^2} = \frac{3}{2M_W^2}\left(1-\frac{4p_T^2}{M_W^2}\right)^{-1/2}\left(2-\frac{4p_T^2}{M_W^2}\right)F(p_T)$$

$$F(p_T) = \frac{1}{\sigma}\int_R dy\frac{d\sigma}{dy}+\left(1-\frac{4p_T^2}{M_W^2}\right)^{1/2}\left(1-\frac{2p_T^2}{M_W^2}\right)^{-1}\frac{1}{\sigma}\int_R dy\left(\frac{d\sigma^+}{dy}-\frac{d\sigma^-}{dy}\right)$$

At the Tevatron, for the valence-valence process at PT=0, precision measurements of the W lepton charge asymmetry reduce the PDF error in the predicted transverse momentum distributions

-> consequently, Aw helps to reduce PDF errors in measurement of Mw.

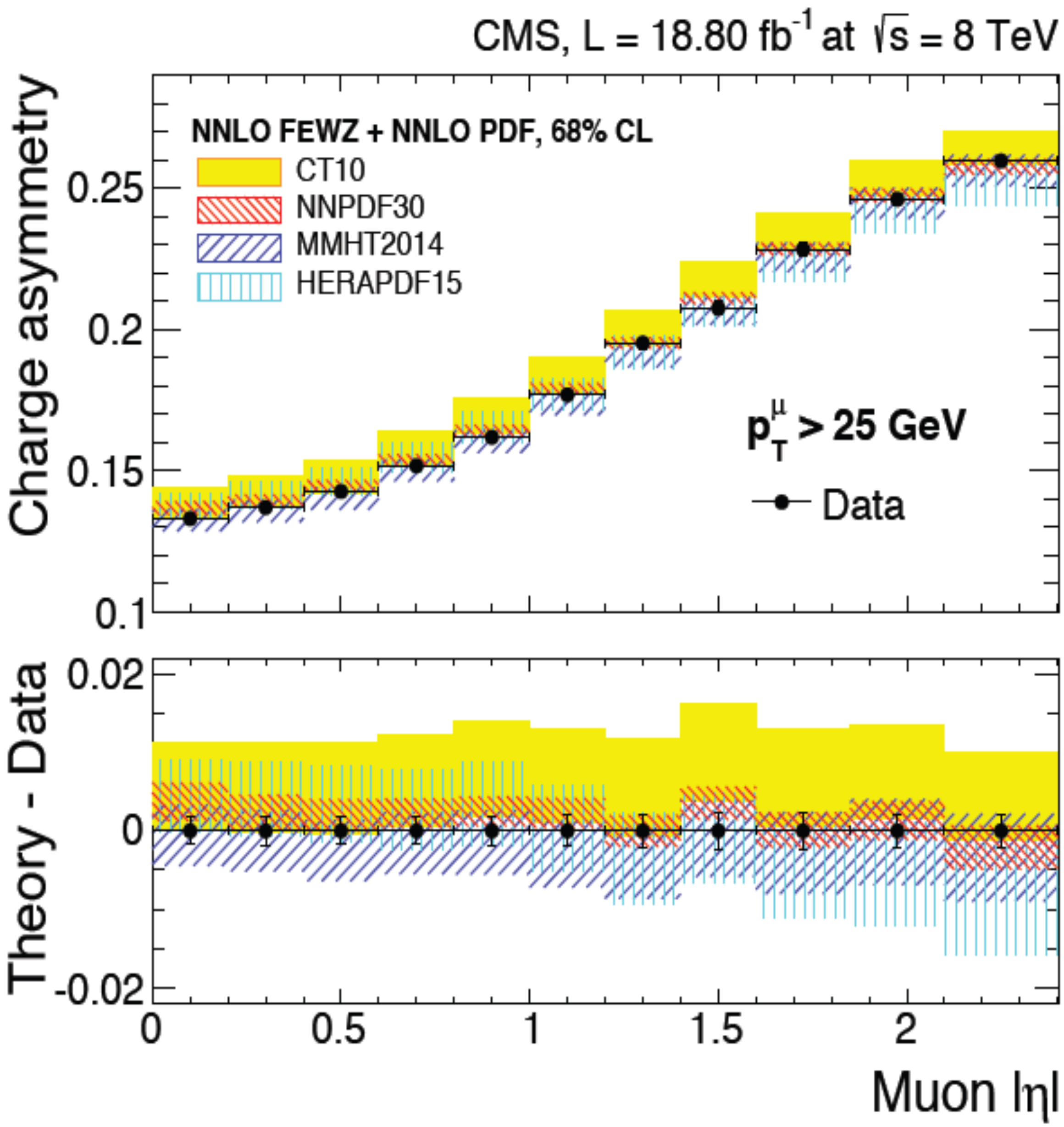
Only PDFs which are consistent with **W lepton charge asymmetry measurements at the Tevatron should be considered.**

$$\left(\frac{W^-}{W+}\right)^{Tev} \approx \frac{d(x_1)\ u(x_2)+s(x_1)\ c(x_2)}{u(x_1)\ d(x_2)+c(x_1)\ s(x_2)} \approx \frac{d}{u}(x_1)/\frac{d}{u}(x_2)$$

Any other data which constrains the quark PDFs in the W and Z region would also help eg . Drell-Yan Afb, (and to a lesser extent W decay lepton differential cross sections dσ/dη , Z rapidity distributions, W/Z cross section ratios etc).

However, asymmetries can have more impact because of smaller experimental systematic errors (and less sensitivity to QCD scale and higher order terms).

Real CMS AfW asym data



8 TeV CMS W asym Data further constrains NNPDF 3.0 PDFs (red) which have included CMS 7 TeV data.

Very few CT10 replicas would be consistent with the CMS 8 TeV W Asymmetry data (no LHC data included In CT10).

CDF combined electron and muon Afb

Source uncertainty in CDF measurement with 9.4 fb^{-1} (electron+muons)	Uncertainty in $\sin^2\theta^{lept}_{eff}(M_Z)$	Uncertainty in $M_W^{indirect}$ (GeV)
Data: Statistics	±0.00042 (stat)	0.020
Data: Energy scale	±0.00003 (syst)	0.001
Data: Backgrounds	±0.00002 (syst)	0.001
Prediction: PDFs	±0.00016 (syst)	0.008
Prediction: QCD EBA (NLO minus LO)	±0.00007 (syst)	0.003
Prediction: QCD scales	±0.00002 (syst)	0.001
All systematics	±0.00018 (syst)	0.009
Total: (stat+syst)	±0.00046(total)	0.023

Uncertainty in Mw direct (2012) 2.2 fb^{-1} (CDF). MeV

0.012 (stat)

0.007 (lepton scale)*
0.003 (Background)

0.010 (PDFs)**
0.006 (Recoil energy)
0.005 (PT W)
0.004 (QED rad)

0.015

0.019

*Will be reduced using new lepton energy calibrations
** Will be reduced with LHC based PDFs

$$\sin^2\theta^{lept}_{eff} = 0.23221 \pm 0.00046$$

On-shell
$$\sin^2\theta_W = 0.22400 \pm 0.00045$$

$$M_W(\text{indirect}) = 80.328 \pm 0.024 \text{ GeV}/c^2 .$$

The PDF errors include constraints from Afb data (which reduce PDF errors in $\sin^2\theta_W$ from 0.00020 to 0.00015)

Reducing PDF errors for $\sin^2\theta_{efff}$ at CDF and LHC

We use the CDF combined e^+e^- $\mu^+\mu^-$ Afb CDF data to constrain PDFs

Ref : A. Bodek. J. Han, A. Khukhunaishvili, W. Sakumoto:" Using Drell-Yan forward-backward asymmetry to constrain parton distribution functions"
arXiv:1507.02470. (**Eur.Phys.J. C76 (2016) no.3, 115**

All PDF groups provide a default (central) PDF set. There are two methods that are used for the determination of PDF uncertainties.

Hessian Matrix: Use a set of eigenvector error PDFs The PDF uncertainties in a measurement are determined by repeating the analysis for all of the error PDF sets, and adding in quadrature the difference in the result obtained with the error PDFs and the result obtained with the default PDF.

Monte Carlo Replicas: Use a set of N (e.g. 100 or 1000) replica PDFs. Each of the PDF replicas has equal probability of being correct. The central value of any observable is the average of the values of $\sin^2\theta_{efff}$ extracted with each one of the N PDF replicas. The PDF error is the RMS of the values extracted using all N replicas.

Standard Extraction of $\sin^2\theta_{eff}$ using PDF replicas

- For every one of the 100 NNPDF3.0 replicas find the $\sin^2\theta_{eff}$ that gives the best fit. (Replicas can also be generated for any PDF set).
- Without any additional constraints, all 100 PDF sets of NNPDF3.0 (or any other set) are equally likely.
- Therefore, the **average** value of the 100 determination of $\sin^2\theta_{eff}$ is the measurement.
- The RMS of the $\sin^2\theta_{eff}$ values from all 100 PDF replicas is the PDF error.

The same procedure can be used to determine the PDF errors in the measurement of Mw.

Monte Replica Method:

$$\langle s \rangle = \frac{1}{N}\sum_{i=1}^{N} s_i \qquad (12)$$

$$\sigma_{pdf} = \sqrt{\frac{\sum_{i=1}^{N}(s_i - \langle s \rangle)^2}{N-1}} \qquad (13)$$

s=$\sin^2\theta$ or Mw.

and the uncertainty in the PDF error is $\Delta\sigma_{pdf} = \frac{\sigma_{pdf}}{\sqrt{2(N-1)}}$

The calculated standard PDF errors will be the same for both Hessian and Baysian (replica) methods
For any given a set of Hessian eigenvector PDFs there is a prescription to generate an arbitrary number of PDF replicas.

The replica method is preferable for two reasons:

1. We can easily add constraints from new data.
2. We can easily find if the new data is consistent or inconsistent with the PDFs.

We use 100 NNPDF3.0 NNLO PDFs (these included LHC data) in the CDF Analysis of $\sin^2\theta_W$.
For these100 replicas: CDF gets $\sin^2\theta_W$ = 0.22401± 0.00042 (Statistical error)
RMS is the PDF error is ± 0.00020 (PDF)

Baysian Reweighting (incorporating new data)

- New measurements can be incorporated into the ensemble without refits
  - Ensemble PDFs are reweighted

$$w_k = \frac{\exp(-\chi^2_k/2)}{\sum_{l=1}^{N} \exp(-\chi^2_l/2)}$$

χ^2_k: between new measurement and prediction with ensemble PDF k

The new result = weighted mean. The new weighted RMS is a reduced PDF error

It is clear how to do this for new results for processes that have been used in previous PDF fits. (e.g. new LHC W asymmetry data)

We now show how we can get both $\sin^2\theta_W$ AND also further constrain PDFs from the same A_{FB} (M) data

A. Bodek. J. Han A. Khukhunaishvili, W. Sakumoto: arXiv:1507.02470 (**Eur.Phys.J. C76 (2016) no.3, 115**

18. G. Watt and R. S. Thorne (MRST), JHEP 08:052 (2012) (arXiv:1205.4024)
19. https://mstwpdf.hepforge.org/random/
20. Walter T. Giele, and Stephane Keller, Phys.Rev. D58 (1998) 094023 (arXiv:hep-ph/9803393).
21. Nobuo Sato, J. F. Owens, Harrison Prosper, Phys. Rev. D 89, 114020 (2014) (arXiv:1310.1089)
22. Hannu Paukkunen, Pia Zurita, "PDF reweighting in the Hessian matrix approach", http://arxiv.org/abs/1402.6623
23. Richard D. Ball, Valerio Bertone, Francesco Cerutti, Luigi Del Debbio, Stefano Forte, Alberto Guffanti, Jose I. Latorre, Juan Rojo, Maria Ubiali, Nucl.Phys.B849, 112 (2011) arXiv:1012.0836.

Here s is a measurement of $\sin^2\theta_W$ (or Mw)

Wi is the weight for each PDF.

$$w_i = \frac{e^{-\frac{1}{2}\chi_i^2}}{\sum_{i=1}^{N} e^{-\frac{1}{2}\chi_i^2}} \quad (14)$$

$$\langle s \rangle = \sum_{i=1}^{N} w_i s_i \quad (15)$$

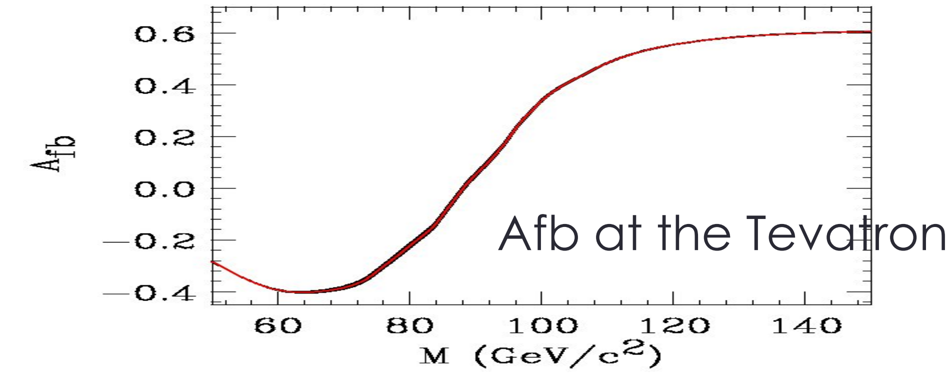
$$\sigma_{pdf} = \sqrt{\frac{\sum_{i=1}^{N} w_i (s_i - \langle s \rangle)^2}{1 - 1/N_{eff}}} \quad (16)$$

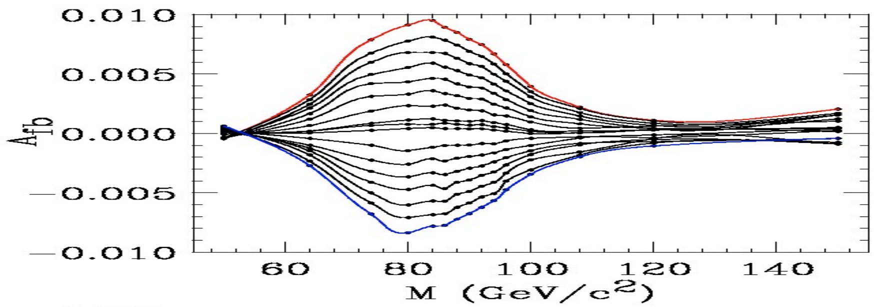
The weights reduce the effective number of replicas from N to N_{eff} where

$$N_{eff} = \frac{1}{\sum_{i=1}^{N} w_i^2} \quad (17)$$

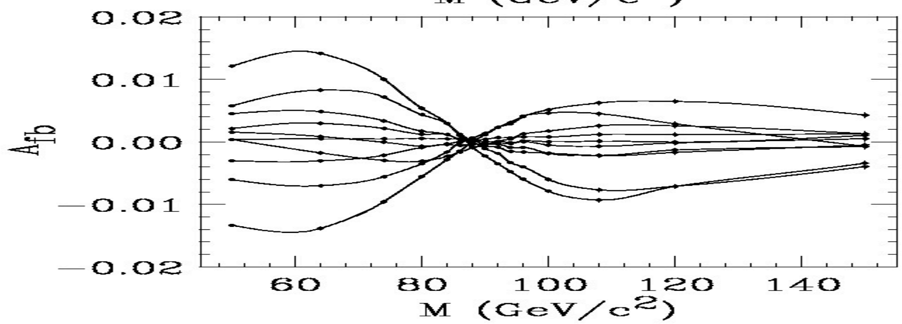
and the uncertainty in the PDF error is $\Delta\sigma_{pdf} \approx \frac{\sigma_{pdf}}{\sqrt{2(N_{eff}-1)}}$.

A Toy MC study of Afb at the Tevatron





lines are variation from different $\sin^2\theta_{eff}$. $\Delta\sin^2\theta_{eff}$ changes Afb mostly in the region of the Z pole.



Lines are variation from different PDFs (NNPDF3.0).
Different PDFs change Afb mostly above and below the region of the Z peak. (different d/u, different antiquarks).

To extract $\sin^2\theta_{eff}$ we change $\sin^2\theta_{eff}$ till we get the best fit to Afb(M).
However, if we use an incorrect PDF it will give a poor fit.

Sensitivity of Afb to PDFs at CDF

Constraints from W lepton Charge asymmetry at the Tevatron
sensitive to slope of d/u **(x range at the Tevatron)**

$$(\frac{W^-}{W^+})^{Tev} \approx \frac{d(x_1)\ u(x_2) + s(x_1)\ c(x_2)}{u(x_1)\ d(x_2) + c(x_1)\ s(x_2)} \approx \frac{d}{u}(x_1)/\frac{d}{u}(x_2) \tag{11}$$

Constraints from Afb at the Tevatron (x range at the Tevatron)
(Afb is diluted by the fraction of antiquarks and the d/u ratio)
Sensitive to the absolute values of d/u and ubar/u,

$$D^{Tev}_{AFB}(d) \precsim [\frac{d}{u}(x_1)]^2 \tag{9}$$

$$D^{Tev}_{AFB}(\bar{q}) \precsim [\frac{\bar{u}}{u}(x_1)]^2 \tag{10}$$

W asym data at CDF reduces PDF errors for Mw measurement but do not reduce PDF errors in the measurement of **$\sin^2\theta_{eff}$** .
However, Afb data reduces errors in both Mw and **$\sin^2\theta_{eff}$** measurements.

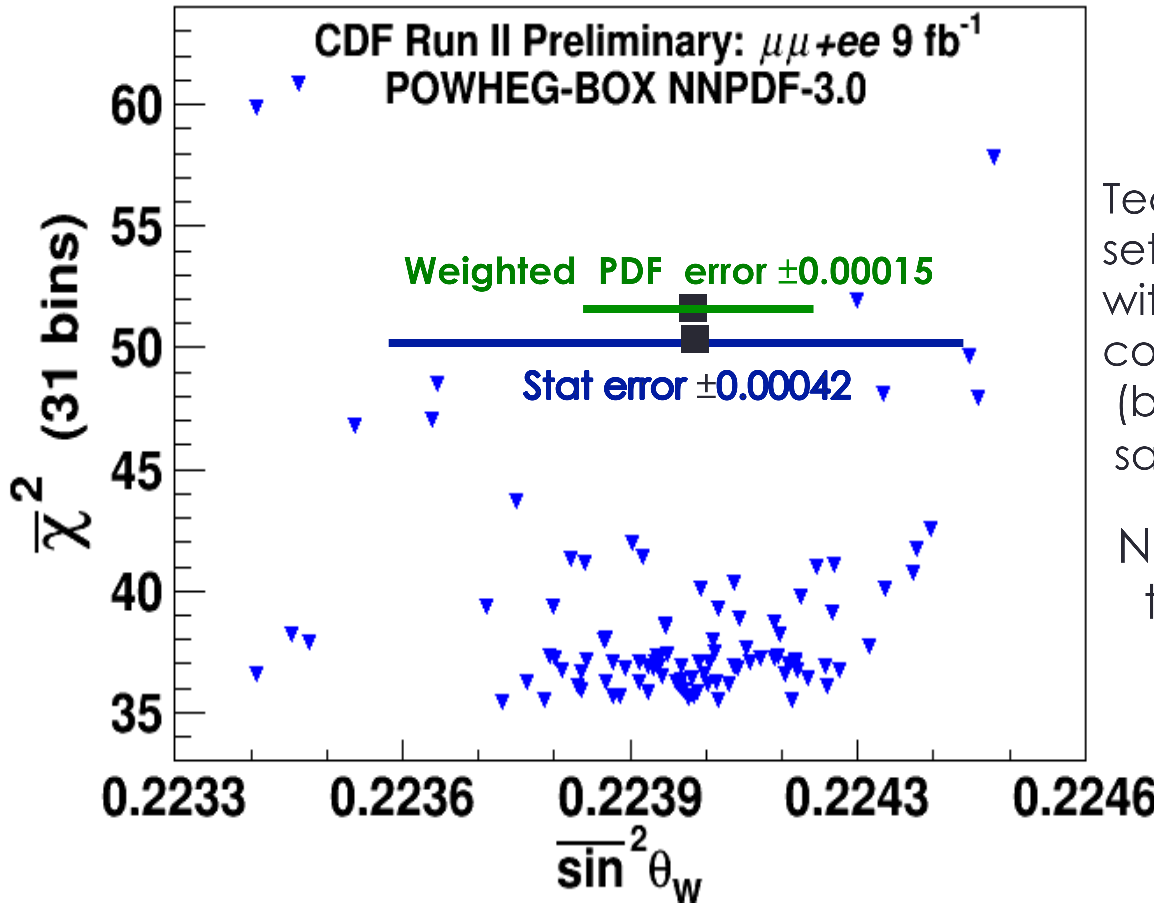
χ^2_{min} versus $\sin^2\theta_W$ for each ensemble PDF:

Weighted Mean → $\sin^2\theta_W$ = 0.22401± 0.00042

Weighted RMS = **reduced PDF error= ± 0.00015 (from ±0.00020)**

Ensemble PDFs are constrained by reweighting

$$w_k = \frac{\exp(-\chi^2_k/2)}{\sum_{l=1}^{N} \exp(-\chi^2_l/2)}$$



100 NNPDF 3.0 (NNLO) replicas

Technique can be used with any PDF set provided the PDF set is consistent with the new data. If the PDF sets are consistent with each other the result (but not the PDF error) will be the same.

NNPDF3.0 NNLO is consistent with the CDF A_{FB} (M) data

These constrained PDFs can be used for other analyses (e.g. direct measurement of the W mass)

Toy Study of PDF Systematics with CMS pseudo-data 26

- PDFs are the dominant uncertainty in the measurement of $\sin^2\theta_W$ at the LHC

- Mainly come in as the uncertainty in the dilution of Afb.

ATLAS result: 0.23080 ± 0.00050(stat) ± 0.00060(syst) ± **0.00090(pdf)**

(Now: Do a Toy MC study with CMS like detector)

Pseudo data with CMS like detector 8 TeV 15 fb^{-1} sample
(7 M reconstructed μμ events) →expected error in $\sin^2\theta_{eff}$:

Expected Stat Error: ± 0.00043
PDF errors with CT10: ± 0.00077
PDF errors with NNPDF3.0: ± 0.00051-→± 0.00026 the new approach

A, Bodek. E t al arXiv:1507.02470 asymmetry to constrain parton distribution functions"
arXiv:1507.02470. (**Eur.Phys.J. C76 (2016) no.3, 115**

Actual CMS sample ar **8 TeV is 19 fb^{-1} sample**
(8.2 M reconstructed μμ events and 6.8 M reconstructed ee events)

Sensitivity of Afb to PDFs at LHC

Constraints from W lepton Charge asymmetry at the LHC
(sensitive to absolute value of d/u)

$$(\frac{W^-}{W^+})^{LHC} \approx \frac{d(x_1)\ \bar{u}(x_2) + s(x_1)\ \bar{c}(x_2)}{u(x_1)\ \bar{d}(x_2) + c(x_1)\ \bar{s}(x_2)}$$
$$\approx \frac{d/u(x_1))}{\bar{d}/\bar{u}(x_2)} \approx \frac{d}{u}(x_1)$$

Constraints from Afb at the LHC (x range of LHC)
Afb is diluted by the fraction of antiquarks and the d/u ratio)
(sensitive to the absolute values of d/u and ubar/u)

$$D^{LHC}_{AFB}(d) \propto\!\!\!\sim = \frac{d(x_1)\bar{d}(x_2)}{u(x_1)\bar{u}(x_2)} \approx \frac{d}{u}(x_1) \qquad (20)$$

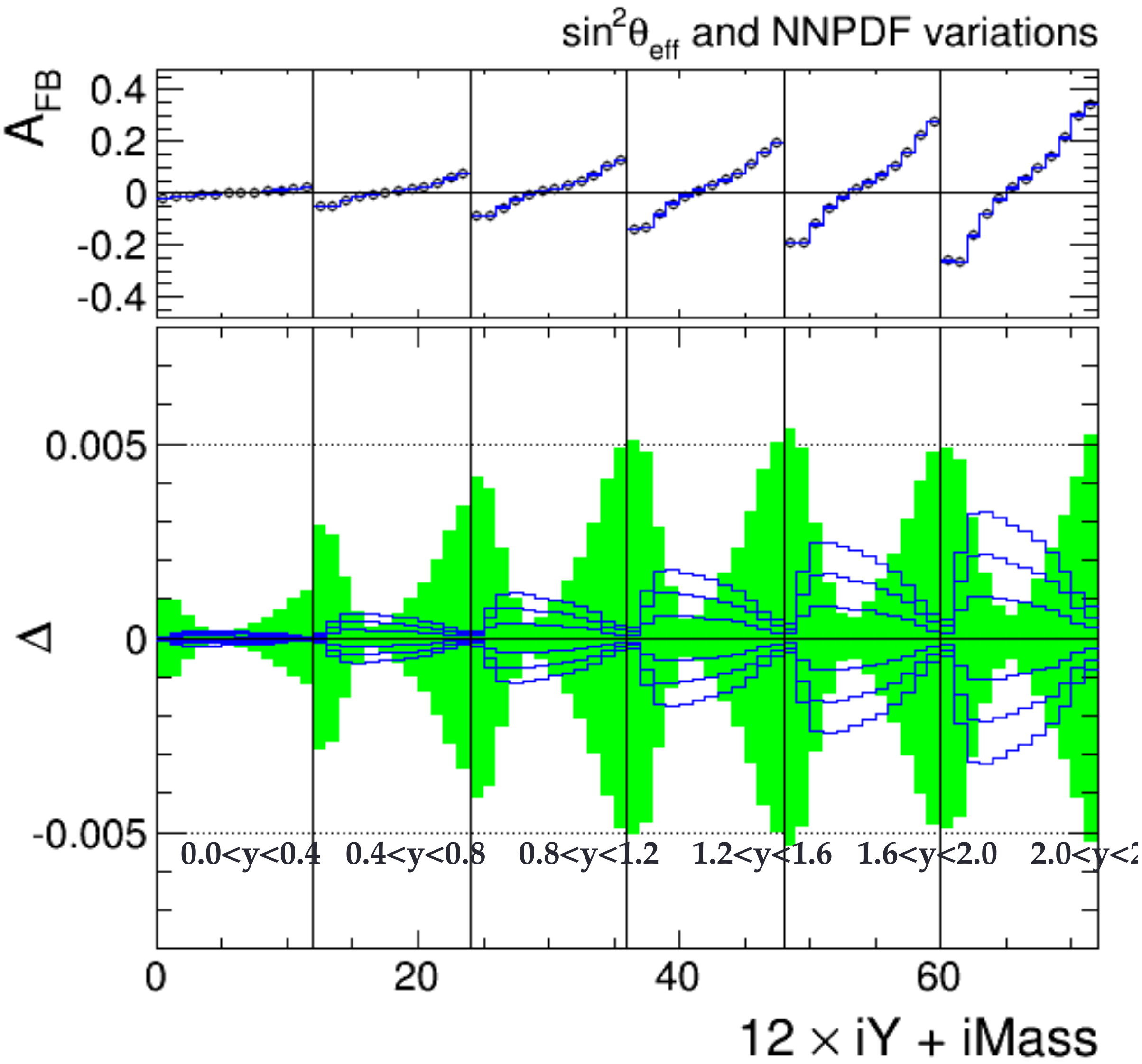
$$D^{LHC}_{AFB}(\bar{q}) \propto\!\!\!\sim = \frac{\bar{u}(x_1)u(x_2)}{u(x_1)\bar{u}(x_2)} \approx \frac{\bar{u}}{u}(x_1) \qquad (21)$$

Both Waym and Drell-Yan Afb at the LHC can be used to reduce PDF errors on both Mw and $\sin^2\theta_{eff}$

PDF vs sin2θeff variations. Toy study CMS-like detector

Green band is RMS variation from different PDFs (NNPDF3.0). Different PDFs change Afb above and below the region of the Z peak.

Blue lines are variation from different $\sin^2\theta_{eff}$ (steps of 0.00040)
$\sin^2\theta_{eff}$ changes Afb in the region of the Z pole. Does not change Afb at high or low mass.
Note that dilution decreases for higher rapidity.
$\sin^2\theta_{eff}$ should be the same – independent of rapidity.
This provides additional information on PDFs



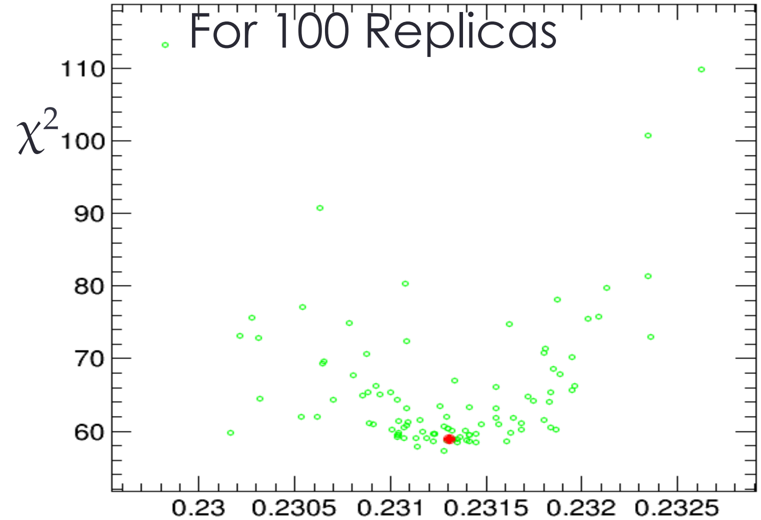
Pseudo-data 7M μμ reconstructed events CMS like detector

Constraining PDFs with Bayesian re-weighting.

Extract **Sin²θ$_{eff}$** for each PDF replica. Plots shown for one pseudo experiment

- We now assign NNPDF replicas weights, based on how well they describe Afb data. weight ~ exp($-\chi^2/2$)

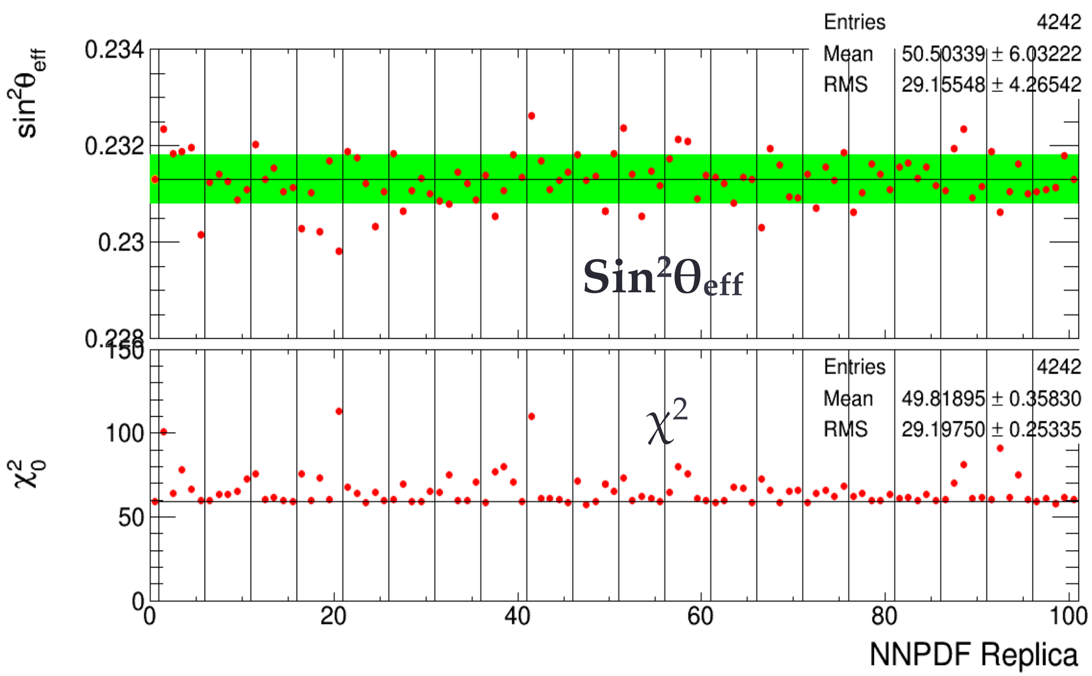
- PDFs with bad χ^2 will have small weights



sin²θ$_{eff}$

Example of one of the 64 pseudo experiments

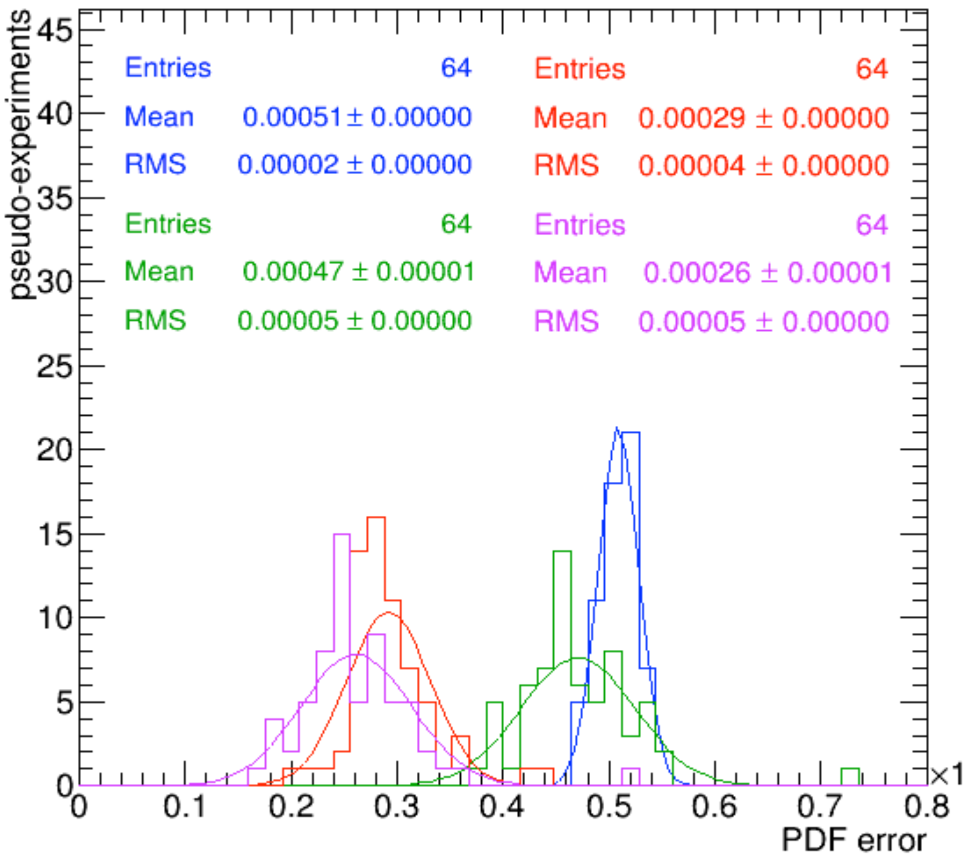
χ^2



For 100 Replicas

PDF errors for **unconstrained** and constrained NNPDF3.0 For the 64 pseudo-experiments CMS-like detector (7M $\mu\mu$ reconstructed events) Errors in $\sin^2\theta_{eff.}$

Stat error 0.00043
CT10 PDF error 0.00077



Method and PDF error

NNPDF3.0 Unconstrained
100 replicas σ_{PDF}= +- 0.00051

NNPDF3.0 8 TeV μ Wasym
constrained weight ~ $\exp(-\chi^2/2)$
σ_{PDF}= +- 0.00047

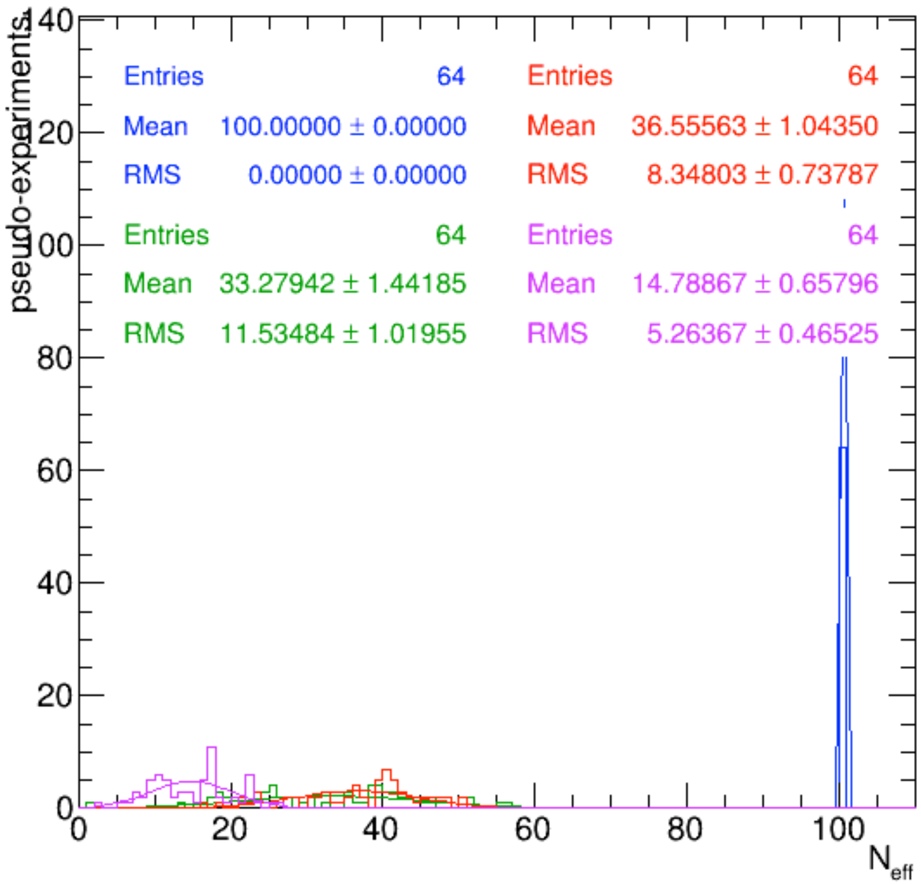
NNPDF3.0 8 TeV $\mu\mu$ AFB
constrained weight ~ $\exp(-\chi^2/2)$
σ_{PDF}= +- 0.00029

NNPDF 3.0 8 TeV combined
constraint from Afb AND
8 TeV W asym: weight ~ $\exp(-\chi^2/2)$
σ_{PDF}= +- 0.00026

*At 8 TeV Afb and 8 TeV W asym data reduce PDF errors to +- **0.00026. Factor of 3 smaller than CT10. Will become even smaller with 13-14 TeV data)***

Afb pseudo 8 TeV CMS data

What is the number of effective replicas for for **unconstrained** and constrained NNPDF3.0 for various levels of constraints.



Method # of effective replicas

No contraints

σ_{PDF}= +- 0.00051 100 replicas

W asym data weight ~ $\exp(-\chi^2/2)$

σ_{PDF}= +- 0.00047 33 replicas

AFB data weight ~ $\exp(-\chi^2/2)$

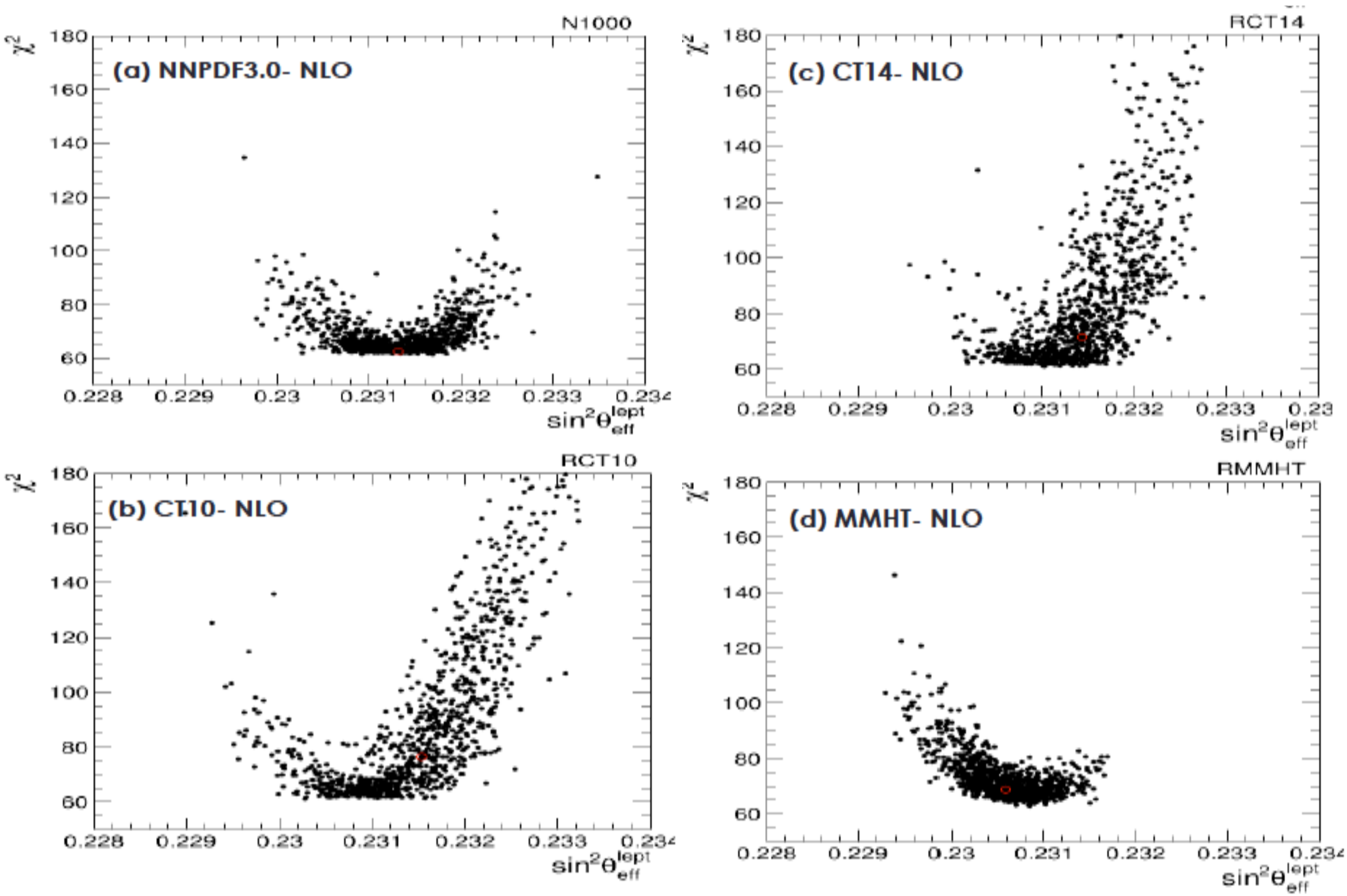
σ_{PDF}= +- 0.00029 37 replicas

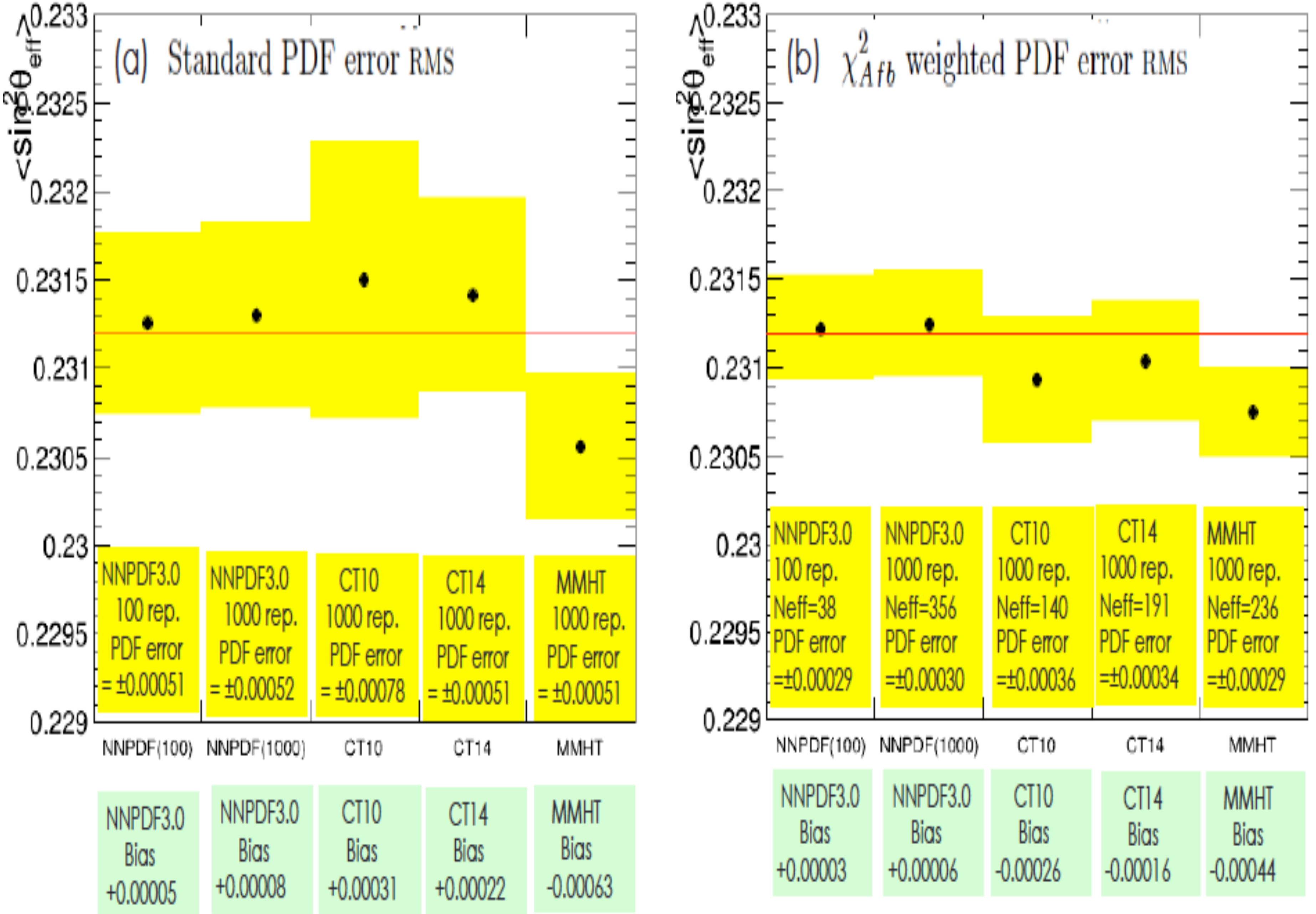
AFB +W asym weight ~ $\exp(-\chi^2/2)$

σ_{PDF}= +- 0.00026 15 replicas

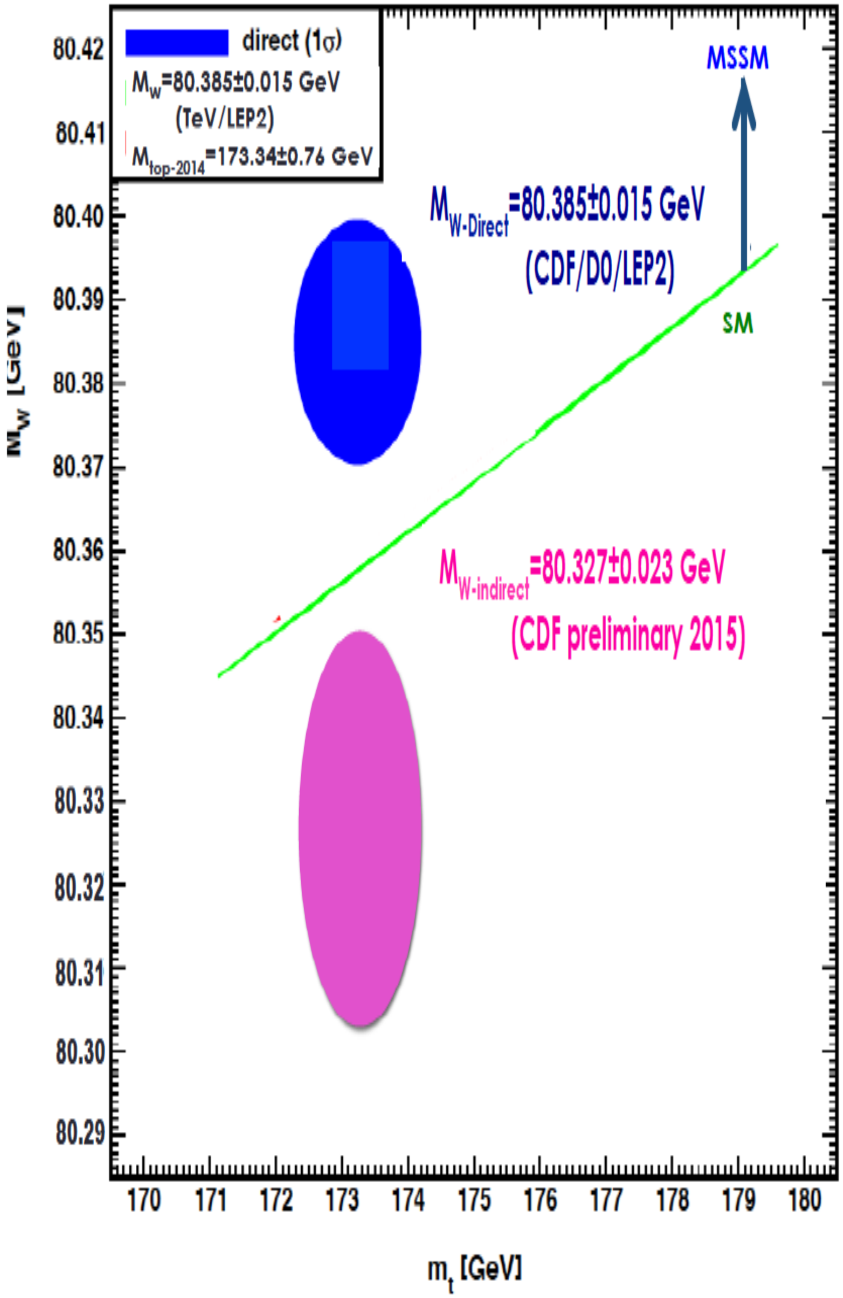
We are repeating the study with 1000 replicas

Afb pseudo 8 TeV CMS data (NNPDF3.0 central)




(a) Standard PDF error RMS
<sin²θeff>
0.233
0.2325
0.232
0.2315
0.231
0.2305
0.23
0.2295
0.229
NNPDF3.0 100 rep. PDF error = ±0.00051
NNPDF3.0 1000 rep. PDF error = ±0.00052
CT10 1000 rep. PDF error = ±0.00078
CT14 1000 rep. PDF error = ±0.00051
MMHT 1000 rep. PDF error = ±0.00051
NNPDF(100)
NNPDF(1000)
CT10
CT14
MMHT
NNPDF3.0 Bias +0.00005
NNPDF3.0 Bias +0.00008
CT10 Bias +0.00031
CT14 Bias +0.00022
MMHT Bias -0.00063
(b) χ²Afb weighted PDF error RMS
<sin²θeff>
0.233
0.2325
0.232
0.2315
0.231
0.2305
0.23
0.2295
0.229
NNPDF3.0 100 rep. Neff=38 PDF error =±0.00029
NNPDF3.0 1000 rep. Neff=356 PDF error =±0.00030
CT10 1000 rep. Neff=140 PDF error =±0.00036
CT14 1000 rep. Neff=191 PDF error =±0.00034
MMHT 1000 rep. Neff=236 PDF error =±0.00029
NNPDF(100)
NNPDF(1000)
CT10
CT14
MMHT
NNPDF3.0 Bias +0.00003
NNPDF3.0 Bias +0.00006
CT10 Bias -0.00026
CT14 Bias -0.00016
MMHT Bias -0.00044

Afb pseudo 8 TeV CMS data



CMS like detector	2016 sample	2017-18 sample
Energy	8 TeV	13-14 TeV
Number of reconstructed events	8.2M $\mu^+\mu^-$ 6.8M e^+e^-	120M $\mu^+\mu^-$ -
$\Delta \sin^2 \theta_W$		
Statistical error	$\pm$ 0.00034	$\pm$ 0.00011
Weighted PDF error	$\pm$ 0.00022	$\pm$ 0.00014
(Stat+PDF) error	$\pm$ 0.00040	$\pm$ 0.00018
$\Delta M_W^{indirect}$	MeV	MeV
Statistical error	$\pm$17	$\pm$5
weighted PDF error	$\pm$11	$\pm$7
(Stat+PDF) error	$\pm$20	$\pm$9

CMS
End of 2015
Analysis in
Progress
Match CDF

CMS
end of 2017
A factor of
2 reduction
in error